

THE BUILT-UP EDGE FORMED ON THE FACE OF THE SINGLE POINT TOOL

AN ABSTRACT OF THE DISSERTATION
SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF DOCTOR OF SCIENCE,
IN THE UNIVERSITY OF MICHIGAN

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JUNE, 1935





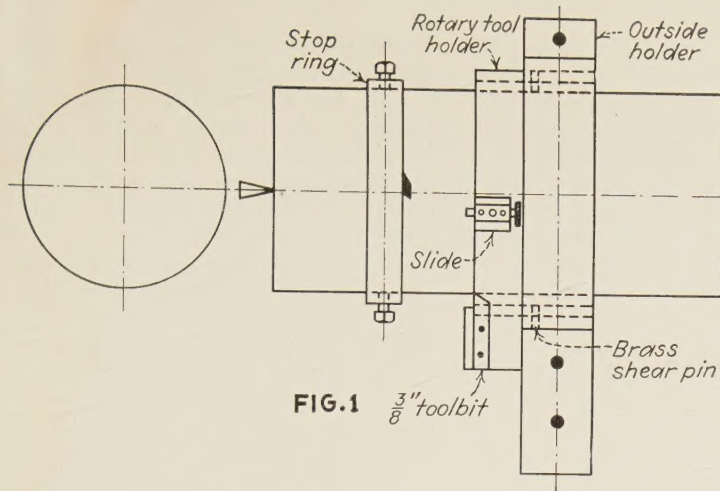


FIG. 1

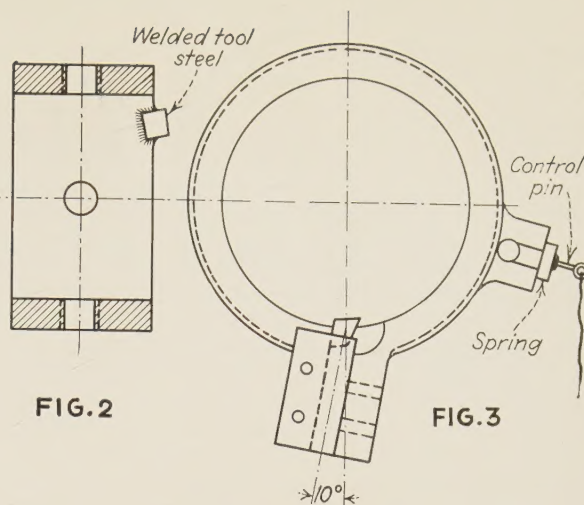


FIG. 2

FIG. 3

Fig. 1—Top view of "rotary toolholder" set-up; by means of this arrangement the dynamic conditions of cutting can be studied because the chip is undamaged when a sample is taken

Fig. 2—The stationary stop ring has a tooth that catches the spring-actuated stop pin in Fig. 3 when the pin is released. This contact shears the brass pins causing the rotary toolholder to revolve with the work until the lathe is stopped

BUILT-UP EDGE on the SINGLE-POINT TOOL

STUDIES of chip formation present many problems that offer fascinating avenues of solution and practical contributions to our knowledge of machinability when they are solved; few of these problems are so little unexplored and so suggestive of results as that presented by the built-up edge phenomenon. Even at the present moment, the necessary scientific background is comparatively undeveloped. The researches of Sawin¹ and Rosenhain² in the early years of the century did little more than to present a few illustrations and lead to a sketchy description of this phenomenon as a sidelight to a study of the structure of materials under mechanical stress. Later studies, beginning with that of Herbert in 1926³, while reflecting improvements in the experimental technique of machinability and leading to a more scientific recognition of the phenomenon and its importance, still treat the built-up edge only as it bears upon their results in a larger field. It is only recently that a satisfactory definition of the built-up edge has been attained.

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It has been my good fortune to devote two full years to the study of the built-up edge. I have investigated it through an original method, and with apparatus invented solely for the purpose. It has been possible to isolate the phenomenon as it actually exists under various cutting conditions; to take microscopic photographs of its various states under these conditions, and to analyze the structure and to determine the relative size of these states, not only in two, but in three dimensions.

First of all, it is necessary for the proper interpretation of these results to sketch lightly some of the theories concerning the built-up edge that have hitherto held the field. Herbert in his pioneer work was the first to describe the built-up edge as the actual cutting implement present when obtuse-angled tools are used on ductile metals. O. W. Boston⁴ more recently described it along similar lines, but with greater accuracy:

It appears that, when a tool starts to cut, the material immediately ahead of the tool point bearing on the face

of the tool is trapped and compressed against the face of the tool by a force which, acting at an elevated temperature, causes it to remain in that location. This material then becomes the built-up edge which is forced into that being cut as the tool advances and appears to be the actual medium for separating the chip from the balance of the metal.

Finally, Ernst and Martellotti⁵ have carried the descriptive definition a little further:

In all studies of chip-flow, one of the most outstanding facts observed is that there exists, under certain conditions, a relatively stationary wedge-shaped body of material which precedes the nose of the tool, and appears to cling thereto, while the main body of the chip flows over it.

My own definition of the built-up edge will be found in substantial agreement with these opinions, although stressing the process from a different angle. The built-up edge is the cutting implement which forms on the extreme edge of the face of the tool, but it consists essentially of plastically deformed particles of the material being cut, and these particles are strained

¹N. N. Sawin, *Über den Schneidwiderstand der Metalle beim Hobeln und Drehen*, Leipzig, 1909.

²Walter Rosenhain, "Crystalline and Amorphous Metals," *Engineering*, 1913, pages 370, 509, 537. Translated in *International Zeitschrift Metallographie*, Vol. V, 1914.

³E. Herbert, "Work Hardening Properties of Metals," *A.S.M.E. Transactions*, Vol. 48, page 705.

⁴O. W. Boston, *Engineering Shop Practice*, John Wiley & Son, New York, 1933, Vol. I, page 116.

⁵Hans Ernst and M. Martellotti, "Metal Cutting: The Formation and Function of the 'Built-up' Edge," *Mechanical Engineering*, August, 1935, Vol. 58, No. 8.

and "set." To elucidate the definition further, we need a short excursus into the theory of plasticity.

When metal is being cut by a tool, the action of the cutting edge depends on the production of myriad stresses over a very small area at a time. These stresses are sufficiently severe to produce plastic flow and local failure of the material. Now, in the material used for my experiments, mild and alloy steel, the mechanism of such flow seems to follow the first law of plastic deformation⁶; that is, the law of "slip" or parallel displacement of the elements of a crystal lattice. Applying these facts, we immediately obtain an illuminating explanation of the mechanism for direct flow and hardening which underlie the phenomenon of the built-up edge.

During chip formation, the sliding over each other of the adjacent slip surfaces naturally produces a local disturbance in the molecular structure of the material much in the same way as rubbing or polishing produces a thin layer of altered amorphous material (work-hardening).

If the disturbance is far-reaching, the molecules will no longer be able to rearrange themselves into the previous crystalline system. Consequently, a

⁶A. Nadai, *Plasticity*, McGraw-Hill Publishing Company, New York, 1931, page 30.

more or less appreciable layer of amorphous metal will be formed on each slip surface. For a short time these layers undoubtedly possess a certain degree of mobility, and act as a lubricant to facilitate further slip along the same gliding planes. Very soon, however, when the disturbed molecules have had time to "set" into the amorphous condition, there appears in each place where slip has taken place a layer of hard, non-plastic, amorphous metal—the built-up edge.

Its behavior is obviously conditioned by the continuation of the forces that caused it. As soon as the layer of hard, non-plastic, amorphous metal is formed, it will prevent any further slip along that particular set of gliding planes. Moreover, since the surface of the *easiest* slip is the one used at the first straining of the material, it follows that more force will be required to effect plastic deformation of the material in the second straining than in the first. This is particularly true because the hard and brittle amorphous films on the surfaces of the previous slip will act as a stiffening skeleton for the whole crystal. Here then is a simple explanation of the built-up edge, and one which will account for the fact that in spite of being of the same material as that which is cut, the

built-up edge can endure and perform the cutting action.

Both this theory, and the practical experimental results upon which it is based, were dependent on the discovery of a correct type of experimental set-up. Its evolution was a matter of some difficulty.

The basic problem was to transfer the dynamic state of actual cutting conditions into a state of immobility. This had to be done in such a manner that the chip would be uninjured, would preserve intact its development at the precise moment of transfer, and would be available for microscopic study. Moreover, the apparatus had necessarily to duplicate cutting conditions commonly encountered in a modern shop. This apparatus finally took the form of the so-called "rotary toolholder."

The construction of this toolholder was quite simple. It consisted of three main parts: (a) the outside holder, (b) the rotary part to revolve with the tool, and (c) the stop ring. The location of these parts in the complete assembly was as shown in Fig. 1. The stop ring was located at a definite distance to the left of the cutting tool supported in the rotary toolholder. The rotary toolholder was inserted in a rigid, stationary outside-holder

A knowledge of the work-hardening action at the cutting point will help prolong tool life and obtain a smoother finish

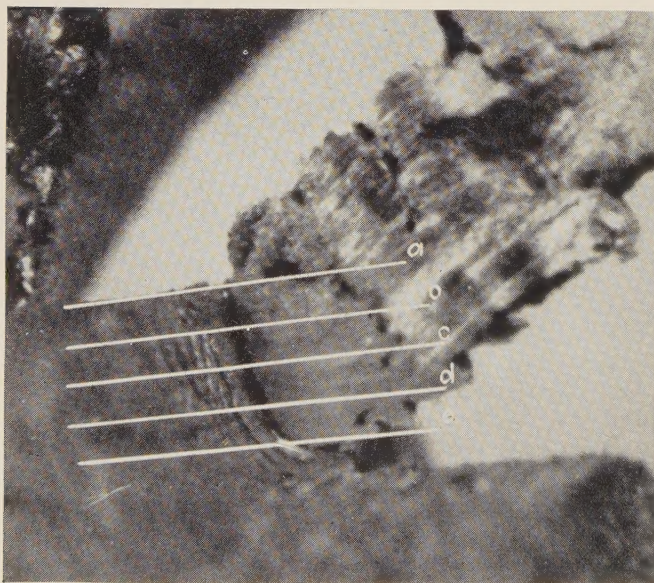


Fig. 4—View of a chip with a built-up edge on it; the direction of the sections at which the built-up edge conformation was studied is shown by the five lines



Fig. 5—Micro picture of the built-up edge for sample A at the outside surface of the chip. Magnification approximately 9.5 times, cutting speed, 34.5 ft. per min.

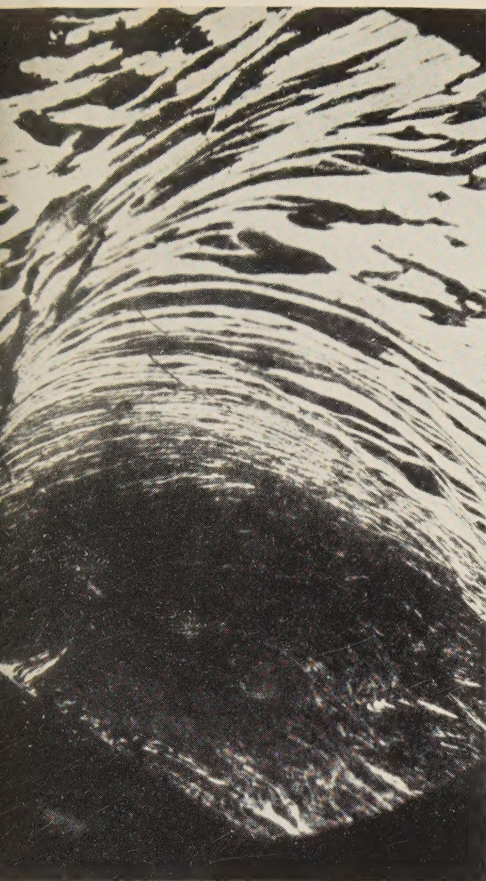


Fig. 6—Micro picture of the built-up edge for sample A at the outside surface, but at a magnification of approximately 70 times. Cutting speed, 34.5 ft. per min.

which performed two functions: first by means of shear pins it held the rotary toolholder stationary during cutting; and second, it acted as a bushing for the rotary toolholder after the pins had been sheared and before the lathe was stopped.

The machine tool used was a Monarch engine lathe, 14 in. by 6 ft., with variable-speed electric motor. The cutting tools were of Motung high-speed steel; $\frac{3}{8} \times \frac{3}{8}$ in. toolbits were used for all tests. Since I was particularly interested in studying the influence of the different cutting conditions upon the built-up edge formation, I took as variables cutting speed, feed, depth, ductile materials, tool shape, and cutting fluid. By making one of these cutting conditions variable and keeping the other five constant, I was able to determine the fluctuations in the built-up edge resulting from the influence of any one factor.

With this apparatus I was able to adopt a standard experimental technique with comparatively few variations. A steel piece was turned and

finished to a 3-in. log, and then cut with annular grooves at equal intervals. The rotary toolholder was set so that the axis of the holder and the axis of the work were in the same horizontal plane during cutting. Cutting then took place in the conventional manner. When, however, the cutting tool approached the rear end of the test ring, the control pin, Fig. 3, was pulled out of its locking position, with the result that the spring-controlled stop pin moved forward instantly and struck the tooth of the stop ring, Fig. 2, shearing the brass pins, Fig. 1, and allowing the aluminum toolholder to rotate freely with the work. The lathe was immediately stopped at this point.

The toolholder was then removed to permit removal of the work material with its sample. The specimen was sawed off and mounted with the aid of Wood's metal in a cup. The outside surface was ground and polished in the usual metallographic manner and etched with 5 per cent nital solution. In order to obtain the third dimension of each sample, I prepared, in the same manner, four sections lying parallel to the first one, Fig. 4. Finally, photo-micrographs and diagrammatic sketches of every section were taken by means of an optical scale tube. Since the graphical method of recording all data proved to be the most objective and accurate, it was used for recording each sample.

To cover the full range of cutting conditions, about 50 samples were prepared, of which two with their micrographs and corresponding diagrams are illustrated. Sample A was taken at low speed—34.5 ft. per min., while Sample B was taken at medium speed of 110 ft. per min. The material was mild steel; the depth of cut, heavy. There is a noticeable difference between the two samples as to the size, shape and structure of the chip and built-up edge: Sample A, Fig. 8, shows a semi-circular shaped edge, while Sample B, Fig. 9, presents one that is flat and layer-like.⁷

1. Influence of Cutting Speed

For SAE 1020, *i.e.*, mild steel, the built-up edge presents three shapes for the following cutting conditions:

Cutting feed 0.040 in. per revolution
Cutting depth 0.125 in.
Tool shape 8-14-6-6-6-15- $\frac{3}{8}$ in. *R.*, *i.e.*, 8 deg. back rake; 14 deg. side rake; 6 deg. end and side cutting angle; 6

deg. clearances; 15 deg. cutting angle; $\frac{3}{8}$ in. radius

Dry cutting

1. A semi-circular shaped, built-up edge formed at speeds up to approximately 50 ft. per min. (a speed range below that used commercially).

2. An acute top-angled wedge shape formed at speeds between 50 and 110 ft. per min. (speeds which are in the commercial range).

3. A flat, layer-like built-up edge formed at speeds of 110 ft. per min. and upward (slightly above those used commercially).

1. Influence of Cutting Speed

Here all cutting conditions were constant except the material cut, which was SAE 2345, and here again the built-up edge shows forms identical with those above. Because of the difference in machinability between SAE 2345 and SAE 1020 as used in Section I, the cutting speeds were necessarily lower: (1) up to 20 ft. per min.; (2) between 20 and 26 ft. per min.; and (3) from 26 ft. per min. and up. It is interesting to note that the conclusions for alloy steel are identical with those for mild steel. Therefore, it would

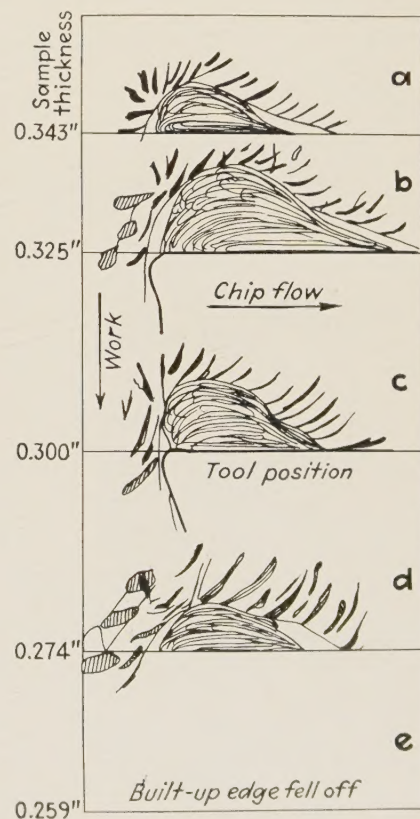


Fig. 8—The thickness and length of the built-up edge for sample A changed at the various sections shown in Fig. 4; magnification, approximately 11 times

⁷Tests at intermediate speeds show a gradual change of form in the built-up edge between these two extremes.

seem natural to assume that since the form of the built-up edge is similar for any two ductile materials, its form might be alike for all ductile materials.

III. Influence of Cutting Fluids

Under the same cutting conditions as for the speed tests, an emulsion and a mineral oil were used as variables. Results showed that the size and shape of the built-up edge are greatly affected, especially in the lower range of speeds. For example, there was a 60 per cent increase in area at the speed of 10 ft. per min. However, at the upper range of speed, the same tendency, although noticeable, was not so marked. Incidentally, there was scarcely any noticeable difference between the outside views of the chips taken at all speeds used in the tests.

IV. Influence of Tool Shape

In this series, the side rake angle was the variable and the rest of the cutting conditions were constant, with the following results:

1. With increase in the side rake angle, the magnitude of the built-up edge decreases.
2. The ratio between the length of

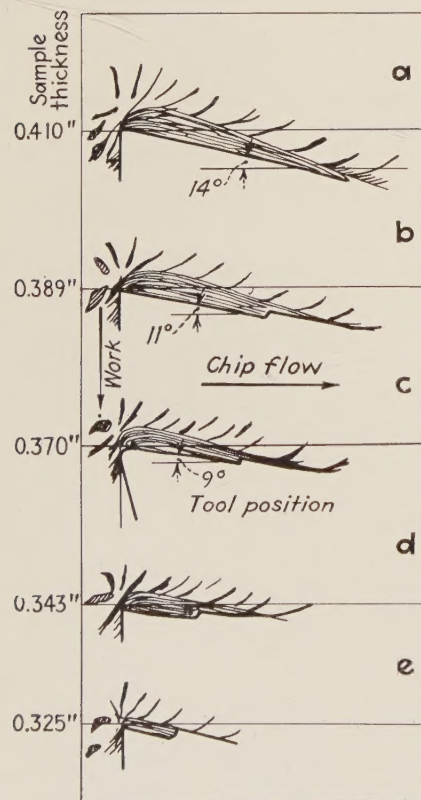


Fig. 9—At the higher cutting speeds the built-up edge for sample B tends to flatten out. Magnification, approximately 11 times

the built-up edge and its height is remarkably decreased. The shape of the edge assumes the appearance of a layer-like structure.

3. With a rake angle of more than 30 deg., the size of the built-up edge drastically diminishes, and gives hardly any protection to the upper surface of the tool.

V. Influence of Depth and Feed

With an increase in the depth of cut, the wedge angle of the built-up edge is increased to an even greater extent than with a similar increase of feed. Moreover, with an increase in depth the relative size of the wedge grows greater than with a corresponding increase in feed for the same chip cross-section.

Considering the extreme complexity of the problem and the lack of scientific background, it is impossible to develop a general, practical formula governing the built-up edge formation. Some general conclusions of practical value suggested by the present findings are worth stating, however:

A. For Heavy Cuts

1. The built-up edge is definitely a protective agent for the cutting tool and prolongs tool life. For obtaining the highest possible protection for the machining of ductile materials with heavy cuts, the following factors will be favorable:

- (a) Moderate speed
- (b) Side rake angle of not more than 22 deg.
- (c) Relatively heavy depth and feed
- (d) Use of a suitable cutting fluid

2. The form of the built-up edge as revealed by the experimental technique described will also reveal the design and suitability of the cutting tool.

3. The finished surface of the material cut is influenced by the size of the built-up edge. With a large built-up edge the finish will be rather rough. For highly finished surfaces the built-up edge should be diminished.



Fig. 7—Micro picture of built-up edge for sample B when the cutting speed is 110 ft. p. m. Magnification, approximately 70 times

B. For Light Cuts

For fine cuts on ductile materials where high finish is desirable, the size of the built-up edge must be decreased, to be effected by:

- (a) an increase in speed
- (b) an increase in the rake angle
- (c) a decrease in depth and feed.

This article is condensed from the author's thesis presented for the degree of Ph.D. in Engineering at the University of Michigan, June, 1935.

Reprinted from

American Machinist

April 8, 1936



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